N71-23515

NASA TECHNICAL TRANSLATION

NASA TT F-13,585

ENERGY STORAGE CAPABILITIES OF SUPERCONDUCTORS IN VIEW OF HIGH POWER DISCHARGE

J. Sole

Translation of "Stockage d'Energie Possibilites des Supraconducteurs en vue des Decharges de Grandes Puissances, Commissariat a L'Energie Atomique, Sarclay, France, Report CEA-R-3243, June 1967, 20 pp.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 APRIL 1971

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ABSTRACT: This report contains an "in depth" treatise on energy storage capabilities of superconductors and the associated energy release at high power. The discussion draws a parallel and comparison between existing energy storage mechanisms (condensers, rotating machines, reactors, batteries, explosives) and the so-called superconductors as seen from French experimental results. Direct comparisons are drawn by using material evaluations, performance equations and cost price ratios.

INTRODUCTION /1*

At the present time, in order to store electric energy and release it at high power in a relatively short time, with a capability of power extension up to about ten nanoseconds, we utilize batteries of condensers. This is the case, for example, for the energization of lasers or for the excitation of plasma experiments....but in spite of the considerable progress that has been made in recent years in the province of dielectrics, the energy storing capability of condensers remains very limited. Today, other solutions are envisaged. So as to be able to compare them in their true perspective we are going to very briefly examine the principal ones. Beginning with condensers, we will terminate with superconductors which we understand....because it is our ideas which have suggested, for some years in France, the first tests of stored energy utilization, with rapid release, in impedances of external use.

CONDENSERS

Energy Storage

Present Capabilities

We use, for example, for supply of experiments on plasmas, condensers of American manufacture. Their characteristics are shown in Table 1.

* Numbers in the margin indicate pagination in the foreign text.

For storing a given energy we assemble the suitable number of condensers.

These condensers correspond to a material that has been selected as possessing interesting characteristics for energy storage (and its release) from among present market material. We can list the important qualities as follows:

density of stored energy : some tens of joules per liter

cost per stored joule : of the order of a few F

TABLE 1. /2

Manufacturer	Capacity C micro-farad	Service Voltage V kilovolt	Stored energy per condenser W kilojoule	Density of stored energy $\frac{W}{V}$ joule/liter	Cost of installed joule Condenser supplied
HAEFELY	15	20	3	72	1.47
G.E.	1	50	1.250	30	4.40
TOBE DEUTSCHMANN	0.85	120	6	23	3.34

When we assemble such condensers, the density of stored energy decreases and the cost per installed joule increases (this is due to cabling arrangement for safety, to the support of the assembly, and in preserving the assembly to assure supply and distribution (of power)).

Present Limits

If we try to determine the maximum energy density that can hopefully be stored with condensers, the problem is presented in the following way:

The total stored energy in a condenser is given by one of the two following expressions:

$$W = \iiint_v \epsilon_o \epsilon_r \frac{E^2}{2} dv = \frac{1}{2} CV^2 \qquad (1)$$

W = total stored energy (joule)

v = total volume of condenser dielectric constituents (m^3)

ϵ_r = relative dielectric constant of the condenser dielectric constituents

ϵ_o = absolute dielectric constant of the vacuum ($1/36\,\pi\,10^9$ units MKSA)

dv = element of volume of the dielectric in which region exists the electrostatic field E (expressed in volts/meter and a function of the coordinates of the element dv)

C = capacity of the condenser thus constituted (farads)

V = charge voltage of the condenser (volts)

We verify that this energy, which is stored in the dielectric according to (1), is only dependent on volume (v), dielectric (ϵ_r), and some value of applied field E.

As a matter of fact we will attain present limits in selecting from among existing dielectrics, the one which interposed in the condenser framework will enable the integral of (1) to determine the maximum value. In the case where the condenser is constituted by frame plates in parallel, the field E is uniform between the plates and integral (1) is written:

$$W = \epsilon_o \epsilon_r \frac{E^2}{2} \iiint_{(v)} dv = \epsilon_o \epsilon_r \frac{E^2}{2} v \qquad (2)$$ /3

This energy W is:

- proportional to the volume of the dielectric v (for a given field and dielectric);

- proportional to the square of field E (in a given volume dv and for a given dielectric);

- proportional to ϵ_r (in a given volume and for a given field).

We can increase it:

- by increasing the volume v of the dielectric, which increases proportionally the encumbrance;

- by increasing the electric field E to which the dielectric is subject. We are then limited by the strength of the dielectric;

- by increasing ϵ_r. We are then limited by the values of ϵ_r for existing materials.

The stored energy per unit volume of dielectric is from (2) equal to:

$$\frac{W}{v} = \epsilon_o \, \epsilon_r \, \frac{E^2}{2} \qquad (3)$$

This energy will now be maximum when the product $\epsilon_r \; E^2$ is maximum. But for a given dielectric this product will be maximum when the applied field E is itself maximum, that is, at the limit equal to the strength E of the dielectric. In examining the principal dielectrics, the most interesting permit, by means of relationship (3), the calculation of maximum energy density $\frac{W_{max}}{v}$ that we can hope to store by unit volume. Table 2 shows the results. We have taken for dielectric strengths, materials which have exhibited highest observed values [1].

TABLE 2.

Kind of dielectric	ϵ_r	E_{max} Volt/meter	Maximum energy density $\frac{W_{max}}{v}$ joule/liter
Printed paper	2.23	1.2×10^8	140
Distilled water	100	1.5×10^7	100
Titanium with Ba or Sr	1800	10^7	790
Polystyrene	2.56	3.1×10^8	1080
Mica	3	1.6×10^8	340
Lucite	3	4×10^8	2190

In practice, the values given in Table 2 will never be reached because of /4 risk of dielectric cracking. The maximum energy that will be stored practically, by unit volume of dielectric, will be, therefore, with existing materials rating less than 3 kj/liter.

With condensers having been utilized for a relatively long time and dielectric having attained, for the present, a high degree of performance, we have little expectation of seeing great improvement in the near future.

Energy Release

The stored energy can be released in any interval of time whatever, provided that it exceeds the proper period of oscillation of the condensers in short circuit. For very great stored energy, if we do not take sufficient precautions, the proper period of the condenser assembly can be higher based on the fact that the connections make up an equivalent induction coil with greater than the inherent voltage (considering discharge distances).

Another intervening parameter in the use of condensers at the peak of their capabilities:

Their duration of life, which happens to be more or less short because:

- the charge voltage and the voltages attained during the discharge are nearer the region of voltage breakdown;

- the reverse voltage attained during the discharge is nearer the maximum admissible reverse voltage;

- the delivered power is higher.

ROTATING MACHINES

Energy Storage

The energy is stored in kinetic form in a rotating, mechanical flywheel. Some practical limits of storable energy can be obtained as a function of the mechanical strength of materials existing at the present time (of weight and dimensions of the flywheel). We will not repeat this work here [2].

Energy Release

An electric machine connected to the mechanical flywheel converts mechanically stored energy to electric energy. The conversion should be made in a very short time to obtain a high power. The rotating parts, rigidly fixed, are subjected to enormous constraints which limit the maximum realizable power.

Naming some characteristics of a self-exciting, asynchronous generator [5] designed to supply intense magnetic fields in transient operation:

- energy storage > 5 MJ

- time of current rise $\simeq 10^{-2}$ s

- limiting voltage 10,000 V

One observes that the time of current rise is relatively long.

This machine is described as possessing the following advantages over the homopolar machine with incorporated transformer (same principal for energy storage, the difference residing in the electric machine which converts the energy): /5

- simplicity of the rotor which is solid and does not involve winding;

- no fluid contacts which avoids some electricity loss;

- capability of immediately obtaining, without a transformer, voltages of high output;

- good efficiency.

On the other hand the following difficulties are significant:

- considerable mechanical constraints appear during the regeneration of energy;

- difficulties in reducing the leakage flow to a minimum between rotor and stator.

From observations of these machines, it should be noted that in electrotechnique the modern tendency is to replace rotating machines with static machines, whenever possible. Moreover, the use of certain rotating machines cannot prevent the use of static transformers. These transformers should, then, sustain all the power. On the other hand, the rotating machine is subject to the wear of its mechanical parts and demands essential maintenance.

REACTORS

They are very limited in power. Electrochemical storage batteries are very superior in this domain at the present time.

STORAGE BATTERIES

The present best storage batteries for the use of great power are made of gold and zinc [3].

Energy Storage

The usable stored energy in the discharge of power is less than 55 Wh/kg for a cell weighing 2.5 kg, volume 1.2 liters, and cost about 5 F.

This represents a stored energy

$$\frac{W}{m} = 55 \times 3600 < 200 \text{ kj/kg}$$

Which represents per unit volume

$$\frac{W}{v} < \frac{200 \times 2.5}{1.2} = 400 \text{ kj/liter of storage battery}$$

The cost per installed joule P is therefore

$$P = \frac{950}{200{,}000 \times 2.5} = 0.002 \text{ f/joule}$$

For very great stored energies, the cost per installed joule increases /6 because of necessary connections and auxiliary installations which are required by storage batteries of major importance.

Energy Release

Under future working conditions, the peak current is of the order of 1600 A per cell at a voltage of the order of 1.2 V; the peak power is therefore of the order of:

$$\frac{16{,}000 \times 1.2}{2.5} = 0.77 \text{ kW/kg}$$

But the duration of storage battery life under these working conditions is limited to 40 operations.

EXPLOSIVES

Energy Storage

Energy storage is of the order of 5 kj/gram.

Energy Release

The practical problems can become considerable if we wish to utilize this energy with a suitable efficiency. In general, it results in the destruction of the apparatus used. For this reason we will not pursue this examination further.

SUPERCONDUCTORS

Since the appearance of the first superconductor materials for high critical fields (about 1960), numerous laboratories have begun the utilization of these materials to achieve windings necessary for obtaining intense magnetic fields. These intense fields, as a matter of fact, set in action important magnetic energies which could cause the explosion of windings and accidents. The principal efforts of these laboratories was then directed, towards the stabilization of these windings by the introduction of quantities of copper in short-circuit (a relatively important and convenient way to protect the winding from transition by induced currents, and limitation of steep gradients in temperature by heat inertia).

By way of example:

- a small cylindrical winding, made in the United States, designed to produce an induction of 100,000 gauss in a volume of some cm^3 and with external measurements of about 12 cm in diameter and 6 cm in height. It stored, as a matter of fact, an electrical energy of 9000 joules;

- another cylindrical coil designed to produce a high magnetic induction in a large volume, with external measurements of about 50 cm in diameter and 50 cm in height. It stored, as a matter of fact, an energy of 1 megajoule.

This already represents energy densities (involuntarily accomplished) that are very superior by some tens of joules per liter to that which can be stored using condensers (Table 1). Furthermore, these coils have not been conceived for storing energy and were not optimized for that purpose. On the other hand, their structure is such that they are incapable of releasing this energy in an external circuit in a relatively short interval of time, and with good efficiency.

Capabilities of Superconductors /7

Energy Storage

If we try to determine the maximum energy density that can hopefully be stored by means of superconductors, the problem is presented in the following fashion:

The total stored energy in a superconductor is given by one of the two following expressions:

$$W = \iiint_v \frac{B^2}{2\mu_o \mu_r} \, dv = \frac{1}{2} LI^2 \qquad (4)$$

W = total stored energy (joule)

v = volume of space included by the magnetic induction B

μ_r = relative magnetic permeability of the space in which the induction B occurs

μ_o = absolute permeability of the vacuum ($4 \pi \times 10^{-7}$ units MKSA)

dv = element of volume of the space in which the occurring induction B (expressed in Tesla) is a function of the coordinates of the element dv

L = coefficient of coil induction of the superconductor circuit (henry)

I = current flowing in the superconductor circuit (ampere)

Since B = 0 in the superconductor (Meissner Effect) this energy W is stored entirely outside of the superconductor material itself, that is, in the space amplexicaul to the coil. But if this space is constituted by the ambient atmosphere (for example, air or vacuum, etc.), it is not encumbered by a densimeter and does not have to be cooled as the superconductor itself. In the final analysis the energy is stored in a space which costs nothing.

Role of the dielectric

Relationship (4) shows that this stored energy W:

- increases with the volume of the dielectric where the induction B is created (the kind of dielectric being given);

- increases with the square of the induction (in a volume dv of a given dielectric);

- is, under these conditions, inversely proportional to the relative permeability μ_r of the dielectric.

The result is that in order to store high energy densities it is not to our advantage to utilize magnetic cores. In effect:

- If we operate at a weak induction B, the numerator B^2 of relationship (4) will be small and the denominator will have a high value because the relative permeability μ_r of the material utilized will be high.

- Or else, if we operate at a high induction B (B > 25 kg), the material utilized will be saturated. Its relative permeability μ_r will then be nearer to 1, that is, the same as that of the ambient atmosphere, if we remove the core.

In each of these two cases we have uselessly introduced a very heavy material (its density being of the order of 6000 times that of air) which will cause some new losses at the time of energy release, by hysteresis and eddy currents. /8

Energy densities that can be stored in the dielectric

In a volume of dielectric dv that is sufficiently small so that the induction power may be considered constant, relationship (4) can be written:

$$\frac{dW}{dv} = \frac{B^2}{2\mu_r \mu_o} \qquad (5)$$

By way of example, the values of the energy $\frac{dW}{dv}$ stored per unit volume of dielectric (air or vacuum) as a function of the different values of the induction B, are shown in Table 3. For the convenience of comparison they have been given in joule/liter of dielectric and the values of induction have been given in kilogauss (1 kilogauss = 0.1 Tesla).

TABLE 3.

$B_{kilogauss}$	$\frac{dW}{dv}$ joule/liter
10	400
20	1 600
50	10 000
100	40 000
200	160 000
400	640 000

At the present time, inductions comprised of between 50 and 100 kilogauss are commonly realized. We still do not know if inductions of several hundred kilogauss will be realized on a large scale and where the limit will be situated. Superconductor capabilities limits will be imposed by the limits of the critical field of the material under the conditions of use. It is very important to note that each time we prepare materials presenting higher critical inductions, the energy stored per unit volume of dielectric increases as the square of the induction.

Of all the existing methods, all the figures given in Table 3 are very superior by some tens of joules per liter to present storage capabilities of some condensers.

The real problem of optimization of energy storage

At the present time superconductor materials are relatively troublesome. Under these conditions, we can have an interest in storing a given energy by not seeking to store it in the minimum volume of dielectric, rather, we would seek to use the minimum quantity of superconductor material.

This problem has been examined [4] in the case where the storage circuit is constituted by a coil winding in torus form. Such a coil winding permits recovery of the same order of magnitude that we would expect with all short coils in avoidance of "end effects" in superconductors and carrying out rigorous calculations. Practically, we will prefer in numerous cases to use short coils corresponding to coil windings more easily realized and carrying fewer encumbrances. We are going to give here only the results of calculations that we have worked out concerning the torus geometry. /9

Figure 1 represents the torus and its axis of revolution (Δ). The torus coil is constituted by means of a superconductor uniformly distributed and of negligible thickness owing to the dimensions of the torus. r_1 and r_2 designate, respectively, the radius of the throat ring of the torus and the radius of a circle of largest diameter.

In order to simplify the text we set up the following:

$$\alpha = \frac{r_2}{r_1} \tag{6}$$

The induction produced by a coil winding is zero at the outside of the torus, and different from zero at the inside. It is a maximum, and the same value, at all points on the throat circle. However the superconductor material is used, it is necessary that the induction be less on the throat circle of the torus, but very near the critical induction of the material.

The critical induction of a superconductor wire is related to the current by a function given as an example by the curve of Plate 1, relative to an intermetallic alloy Nb, 25 percent Zr. This function depends on the way in which the superconductor is used, and differs according to variation of a piece of rectilinear wire or superconductor wire coil. In the latter case we observe a "diminution effect" phenomenon which has been the object of numerous studies conducted by researchers who concentrate on the production of magnetic fields.

Here are results that we have obtained (4): (the numerical applications which follow these results are based on an actual cable of 7 strands Nb, 25 percent Zr (U.S. superconductor) and the characteristics shown in Plate 1, although the Nb_3S_n is more interesting and we will speak of it at the end of this account).

Geometric dimensions of the torus:

$$r_1 = 2\sqrt[3]{\frac{\mu_o}{4\pi^2}}\ \sqrt[3]{\frac{\alpha+1}{(\alpha-1)^2}}\ \sqrt[3]{\frac{W}{B_m^2}} \qquad (7)$$

r_1 = in meters (see Figure 1)
μ_o = $4\pi \times 10^{-7}$ (units MKSA)
α = defined by relationship (6)
W = total stored energy (joule) /10
B_m = maximum induction (Tesla) according to the material characteristics (for example, Plate 1 for Nb, 25 percent Zr)

This relationship connects the form and geometric dimensions of the torus (α and r_1) to the total stored energy W and to the characteristics of the material (B_m in the conditions utilized). The calculation is approximate (W is deduced from the mean induction).

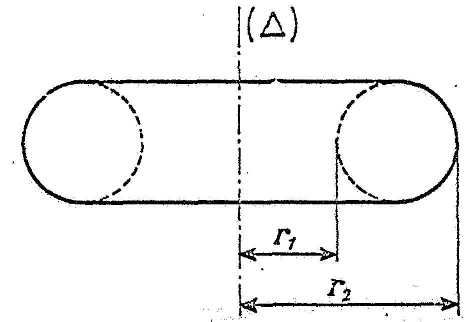

Figure 1. Torus.

In this expression the first factor is constant and the second is a function of α, some example values of which are listed in Table 4.

TABLE 4.

α	1.5	2	3	5	10
$\sqrt[3]{\frac{\alpha+1}{(\alpha-1)^2}}$	3.42	1.44	1	0.72	0.51

<u>Density of energy in stored volume (energy stored per unit volume of superconductor)</u>

$$\frac{W}{v} = 1450 \sqrt[3]{\frac{\mu_o}{2\pi^2}} \sqrt[3]{\frac{\alpha-1}{(\alpha+1)^2}} \; I_m \sqrt[3]{B_m} \sqrt[3]{W} \qquad (8)$$

$\frac{W}{v}$ = density of stored energy (injoule per liter of the superconductor)

I_m = maximum current (ampers) in the superconductor from the characteristics of the material

B_m and W as in formula (7)

<u>Density of energy in stored mass (energy stored per unit of mass of the superconductor)</u>

$$\frac{W}{m} = \frac{1450}{\rho} \sqrt[3]{\frac{\mu_o}{2\pi^2}} \sqrt[3]{\frac{\alpha-1}{(\alpha+1)^2}} \; I_m \sqrt[3]{B_m} \sqrt[3]{W} \qquad (9)$$

$\frac{W}{m}$ = mass density of stored energy (in joule/kg of superconductor

ρ = specific mass of superconductor (kg/dm^3)

In the case where the specific mass of the superconductor is near that of niobium (ρ = 8.7 kg/dm^3) relationship (9) becomes: /11

$$\frac{W}{m} = 167 \sqrt[3]{\frac{\mu_o}{2\pi^2}} \sqrt[3]{\frac{\alpha-1}{(\alpha+1)^2}}\, I_m \sqrt[3]{B_m} \sqrt[3]{W} \qquad (10)$$

Duration of Storage

If we keep the temperature at a low value or equal to that for which the system has been calculated, the duration of storage is practically unlimited for a conveniently mounted storage system (joining suitable superconductors, if necessary and stabilization of excursion flux).

Cost of stored installed joule

$$P = 2 \sqrt[3]{\frac{2\pi^2}{\mu_o}} \cdot \sqrt[3]{\frac{(\alpha+1)^2}{\alpha-1}} \; \frac{1}{I_m \sqrt[3]{B_m}} \; p \cdot \frac{1}{\sqrt[3]{W}} \qquad (11)$$

P = cost of stored installed joule (F/joule)

p = unit price of superconductor material (F/meter of cable, or of wire, etc.)

μ_o, α, I_m, B_m, W as described above

This relationship connects:

the price of stored installed joule

to the geometric form factor of the storage torus $\sqrt[3]{\frac{(\alpha+1)^2}{\alpha-1}}$

to the electric characteristics of the superconductor $\frac{1}{I_m \sqrt[3]{B_m}}$

to the unit price of the superconductor p

and to the total stored energy $\frac{1}{\sqrt[3]{W}}$.

The form factor $\sqrt[3]{\frac{(\alpha+1)^2}{\alpha-1}}$ of the torus is minimum for $\alpha = 3$ (that is, $\frac{r_2}{r_1} = 3$). It is then equal to 2 (which gives the lowest value to P), but varies very little when α varies in a certain range as shown in Table 5. /12

TABLE 5.

α	1.5	2	3	5	10
$\sqrt[3]{\frac{(\alpha+1)^2}{\alpha-1}}$	2.32	2.08	2	2.08	2.37

Practically, for the convenience of making coils, we are not able to choose α too large (that is, r_2 too different from r_1) nor too near to 1, because the torus form factor then increases rapidly and introduces too large variations in price for a slight dispersion in the manufacturing. We see, then, the values of the torus form factor remain near 2. Relationship (11) is written under these conditions:

$$P = 2000 \cdot \frac{1}{I_m \sqrt[3]{B_m}} \; p \; \frac{1}{\sqrt[3]{W}} \qquad (12)$$

with the same notations and units as in (11).

Therefore:

- If we try to store the energy by means of installations having as little encumbrance as possible: it will be necessary to minimize r_1 (formula 7) as much as possible, and therefore, for a given energy W to operate at an induction B_m as high as possible (Table 1), and to choose a material possessing values of B_m as high as possible. But under these conditions, the price P (formula 11) of the stored installed joule will not be minimum because the product $I_m \sqrt[3]{B_m}$ will not then generally be a maximum.

- If we try to store the energy by means of installations which are as little troublesome as possible: it will be necessary to choose a characteristic operating point of the material such that the product $I_m \sqrt[3]{B_m}$ is maximum. The necessarily selected material will be, among the possible materials, that one in which the ratio of unit price p to the maximum value of the product $I_m \sqrt[3]{B_m}$ will be minimum (formula 11). The minimum value of this ratio defines the compromise to make between the price of the materials (p low) and their performance ($I_m \sqrt[3]{B_m}$ high). The minimum value of this ratio will not correspond, generally, to the maximum value of B_m. This signifies that the encumbrance of the torus (formula 7) will not, then, be a minimum.

Energy Release

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We can, for instance, accomplish this according to the method given in reference [6].

An induction coil acts as a current generator (when a condenser acts as a voltage generator). An induction coil superconductor is even better adapted than a condenser for supplying a dissipating circuit in which the impedance varies during the discharge, such as a tube flash or a plasma. Besides, we can very easily obtain un-oscillating, diminished discharges, even in some rapid discharges of the order of microseconds [9] [7], which can be very interesting just for the supply of gas tubes and plasmas.

The adaptation of impedance is easy to do on a dissipative charge. For example, (relationship 4) a given energy W can be stored in an induction coil L (relatively weak and constituted by numerous superconductor cables in parallel) traversed by a high total current I, or entirely in an induction coil L (relatively high and constituted by numerous turns of the same cable in series) under a current which can then be relatively weak. Thus, we will be able to realize a superconductor circuit which will store the desired energy directly at total current I that we wish to obtain at the time of the discharge.

The voltage appearing at the terminals of the induction coil at the time of the discharge has for an expression $V(t) = L \frac{dI(t)}{dt}$. We will be able to obtain much higher voltages at the beginning of the discharge, as we will open the storage circuit more rapidly and the impedance of the charge will be higher.

Or again, the energy W can be stored in an induction coil L of a given value under a given current I, and released by the intermediary of a conductor circuit connected by induction to the superconductor storage circuit; the assembly functioning exactly as a transformer (without iron) at the time of the discharge. Thus, we will be able, whatever the values of induction and storage current, to obtain at the terminals of the connected conductor windings....very high voltages at very weak currents (a great deal higher than we can obtain with batteries of condensers). In particular, similar circuits will be able to release directly, either voltages or extremely high currents, in the same time as the very high voltages and very intense currents, by the intermediary of different secondary circuits directly connected to the superconductor storage circuit. We have effected in these possibilities, numerous experiments which have not yet permitted us to suspect the limits.

We have seen above that the release of this energy would be accomplished in a very short time. We have successfully realized, at weak energies, some tests with times of the order of microseconds following a detailed study of the mechanism of phenomena [9] [7]. This problem does not present particular difficulties.

It happens that it is possible to establish the release of stored energy under considerable power....and it is difficult at the present time to estimate the limits. It appears that aside from explosives, each other means of storage cannot be competitive on the same power level with superconductors. Besides, when energy is released in dissipative charges some very high yields can be obtained and we will be able to cite our tests at weak energies attaining yields of nearly 100 percent [9].

Example of possible realizations

Plate 1 shows the characteristic I_m (B_m) of the material (Nb, 25 percent Zr) which has been used for the numerical applications; in the table above we have grouped the values of the product $I_m \sqrt[3]{B_m}$ (which occurs in relations 8, 9, 10, 11, 12) for different values of I_m and B_m supporting the characteristic I_m (B_m). We can state that the underlined characteristic relative to Nb_3S_n should give some higher values to the product $I_m \sqrt[3]{B_m}$. The Nb_3S_n in question is, therefore, more interesting than Nb, 25 percent Zr, which we have used as an example con- /14
cerning the density of stored energy. The price per installed joule (at the condition that the unit price of Nb_3S_n does not exceed by too much that of Nb, 25 percent Zr), the diminution of storage coil dimensions (formula 7) B_m,....can attain higher values for Nb_3S_n.

In the case of Nb, 25 percent Zr taken as an example, we establish that the product $I_m \sqrt[3]{B_m}$ is maximum and practically constant for B_m between 5 and 40 kilogauss. If we wish to reduce the price of the installed joule to a minimum, it will be necessary to conceive the coil functions for this region, and if we wish at the same time to have a coil as little encumbered as possible, it will be necessary to choose the induction B_m as high as possible, (relation 7), that is, $B_m = 40$ kilogauss if we do not wish to raise the price of installed joule. We see under these conditions of optimization that the region of material use is different from that which corresponds to the attainment of intense magnetic fields.

Plate 2 shows some numerical results relative to the respective storage of 10^6 and 10^8 joules by means of Nb, 25 percent Zr, whose characteristic is given on Plate 1. (In using Nb_3S_n we would obtain geometric dimensions very much less than these values.)

Plate 3 compares the price of the stored installed joule as a function of the installed energy, between electrochemical batteries, condensers and superconductors.

For batteries the price per joule increases at the same rate as the stored energy because of the connections which become more and more troublesome (if we wish to continue to obtain the same specific for each element in proportion to increasing the total capacity of the battery.

For condensers it is also apparent that connection difficulties begin with a certain stored energy level.

For the superconductors the price per installed stored joule is given by relation (11) and decreases as the cube root of the installed energy; if we add the price of cryogenic apparatus necessary (liquid helium and cryostat, etc.) for compensating the loss of heat, it is necessary to state that the greater the installed energy....the greater the increase in price which results when the cryogenic is weak, because if the installed energy depends on the volume of the storage circuit the refrigerating loss depends as a first approximation on the exterior surface of the circuit.

Material optimization

A material will be the more interesting if it permits a given energy storage at a lower price and with less encumbrance. According to the utilization made, the compromise to adopt between price and encumbrance will be different. Of all the ways that are possible, we should reference formula (7) concerning encumbrance, and formula (11) concerning the price of the stored joule.

Performance and price of material

For convenience, material must be used at less than 4.2 degrees K (temperature of boiling liquid helium under normal pressure).

We have already seen that in order to make r_1 (formula 7) minimum, we must make use of a material which will permit the attainment of inductions B_m with values as high as possible. In order to make P (formula 11) minimum, it is necessary that the expression $\frac{p}{I_m \sqrt[3]{B_m}}$ be minimum. It is necessary, therefore, to use a material of which the unit price p divided by its electrical performance ($I_m \sqrt[3]{B_m}$ maximum) is minimum.

It is not necessary to eliminate the use of several different, judiciously arranged materials in order to satisfy the conditions in which r_1 and P are as low as possible. /15

Forming: the material will be able to be used in the form of wire, cables, ribbons, sheets or coatings. The choice will be made as a function of the cost price of installed joule (formula 11) and of the electrical stability obtained.

The superconductor should be isolated, incased or not incased in a material that is a conductor of electricity and heat, since it will have a unique function of storage or be used as a circuit breaker. In this last case it is required that the material possess, in the normal state, a resistance as high as possible for permitting the introduction of a resistance as high as possible, into the storage circuit after "opening" [8].

Mechanical properties: It should be sufficiently solid (for example, at 100 kg it exerts on the coil a magnetic pressure of the order of 400 kg/cm^2 which extends the axial compression and makes it crack radially. This problem is well known in the production of intense magnetic fields).

It should be sufficiently workable: If it is a question of wire, cables, ribbons and sheets, it is necessary that the reel mechanism be furnished. If it is a question of thin coatings it is necessary that a spreader on convenient supports be furnished.

New Perspectives

It is useless to emphasize the interest which results from the discovery of new materials or of materials possessing new characteristics, usable for example at higher temperatures or possessing more critical pressure characteristics.

It is necessary to note that the interesting materials have only been used since about 1960 (for the production of magnetic fields) and that in some years considerable progress has been made; also, that these questions are poorly understood along with the new technology.

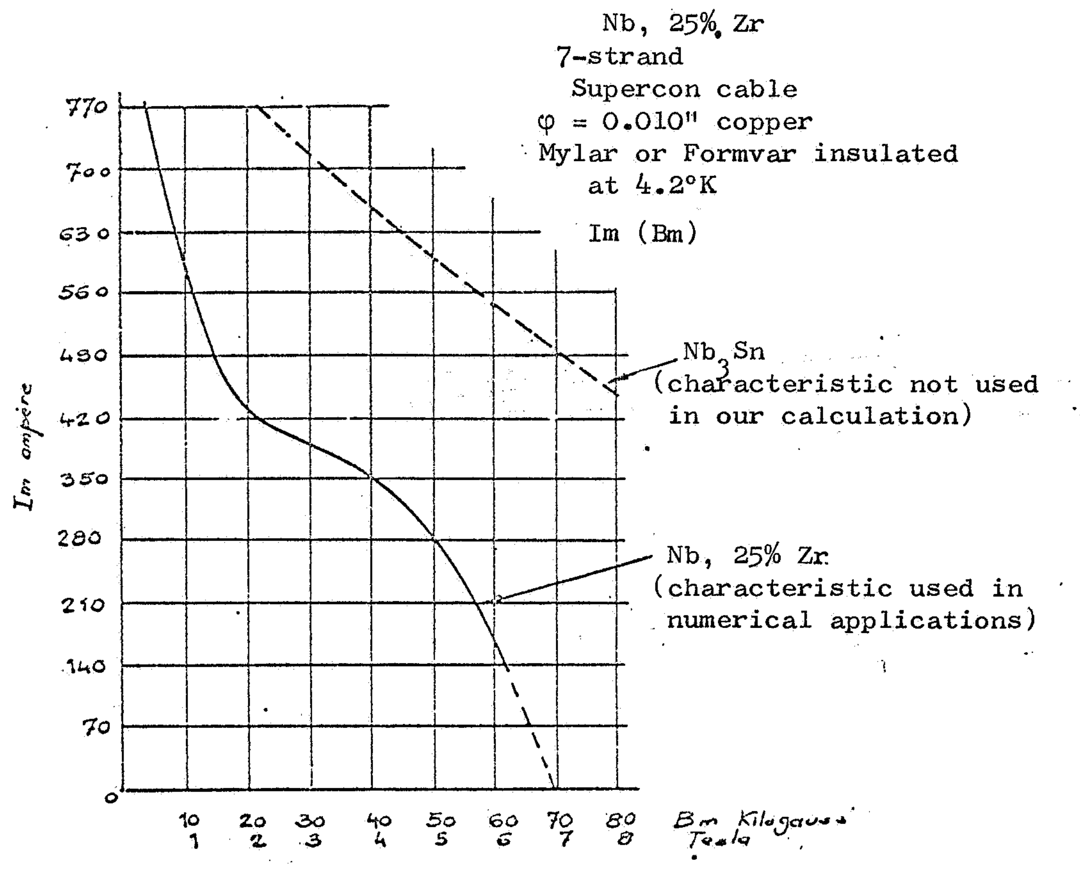
On the other hand, there are years in which we have envisaged the exploitation of thin coatings. Some tests have already been started [10]. They should permit a considerable increase in the storable energy density per unit mass of the superconductor and to lower proportionately the cost price of stored installed joule while increasing the stability of the system.

As of now, superconductors actually permit the conception of storage circuits and release of energy having very different configurations and characteristics from those that we can conceive with condensers. We can, for example, directly envisage experiments in which there would not be connections between generator and energy receiver, and where the generator and receiver would have a common part or would be combined. We cannot, for example, envisage such experiments at very great energies with some condensers because in order to store important energy by means of condensers, and avoiding the use of unrealizable storage voltages, we are bringing into use high capacitances of the order of μF, and these capacitances are very superior to the proper capacitance of a circuit confining a plasma, for example. This is not the same for the induction coil [11].

CONCLUSION

The present concept of storage and energy release is saturated with old ideas, which, as a matter of fact, have been created over the years as the measure of existing energy storage....the superconductors, starting from now, put at our disposition entirely new solutions and even though it is premature to tell, these same superconductors have surprises in store for us.

Plate 1. Characteristics of Supercon's (USA) Nb, 25% Zr



Im ampere taken from the curve	Bm Tesla taken from the curve	$\sqrt[3]{Bm}$	Im $\sqrt[3]{Bm}$
700	0,5	0,79	556
560	1	1	560
420	2	1,26	530
385	3	1,44	554
350	4	1,59	556
280	5	1,71	478
140	6	1,82	255

550

Plate 2. Example of realization with the Nb, 25% Zr cable (USA)

Conditions under which used: BM = 4 Tesla (according to Plate 1).

Im = 350 ampere

geometry of torus: $\alpha = \frac{r_2}{r_1} = 2$

price of cable: p = 15 NF/meter

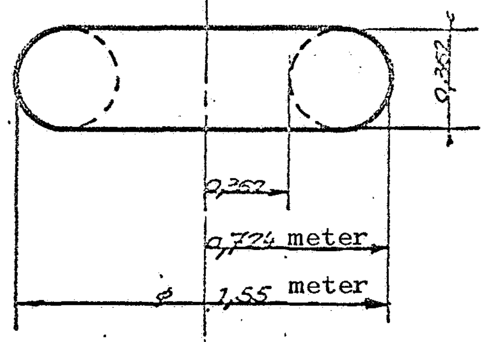
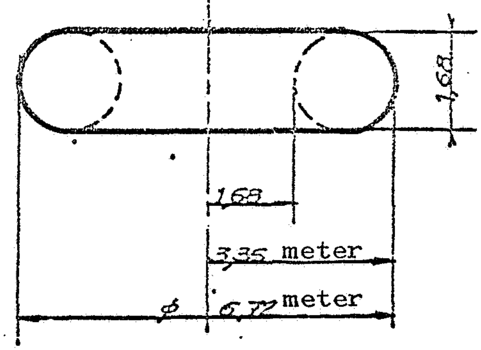
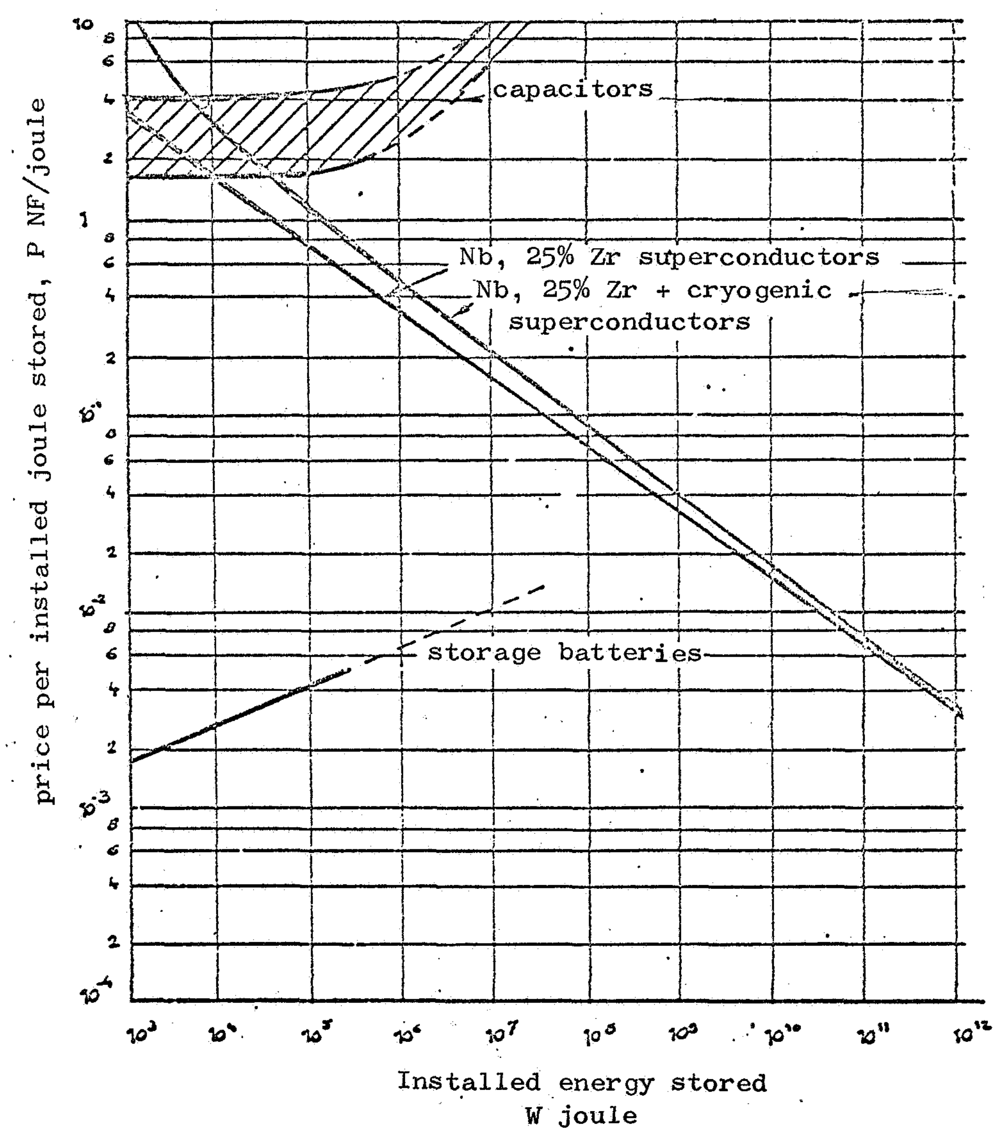
Total energy supplied W	Diameter of the throat of the torus according to Eq. (7), r_i	Energy stored per liter of superconductor according to Eq. (8) W/v	Price per installed joule stored according to Eq. (12), P	Dimensions of the torus according to Eq. (7), in meters.
10^6 Joule	0,362 meter	91000 Joule/ liter	0,55 NF/Joule	→ 
10^8 Joule	1,68 meter	420000 Joule/ liter	0,12 NF/Joule	→ 

Plate 3. Price per installed joule stored as a function of installed energy.

Comparison between: the electrochemical storage batteries Ag, Zn;
the capacitors;
the superconductors;

(only the capacitors and superconductors will liberate energy at very high power)



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Translated for the National Aeronautics and Space Administration under contract NASw-2038 by Translation Consultants, Ltd., Arlington, Va.